

MOVING MAGNET TYPE PLANAR MOTOR CONTROL

FIELD OF THE INVENTION

5 The invention relates to planar motors. More particularly, the invention is related to a control system for a moving magnet type planar motor.

BACKGROUND OF THE INVENTION

Precision systems, such as those used in semiconductor processing, 10 inspection and testing, often use linear motors for positioning objects such as semiconductor wafers. Conventional precision systems include separate, stacked stages that permit movement along perpendicular axes (*i.e.*, an “X” stage stacked on a “Y” stage). These systems typically are complex, heavy and inefficient in operation. Improved object positioning, particularly for use in lithographic instruments, has been realized through the 15 use of planar motors, which advantageously permit simplicity in design, weight savings, as well as enhanced precision and efficiency. Such a linear or planar motor, in principle, operates in accordance with the Lorentz law, which relates the force on a charged particle to its motion in an electromagnetic field. An object such as a stage in a lithography system may be translated or propelled using the electromagnetic force generated by a wire or coil 20 carrying an electric current in a magnetic field. The planar motor provides a single stage to replace conventional stacked stages, with the stage being electromagnetically suspended or levitated for enhanced performance and versatility.

Planar motors typically include a magnet array and a coil array. Several basic designs for planar motors are known, and are distinguished based on which of the 25 components are positionally fixed and which move with respect thereto. In a first design, commonly referred to as a “moving coil type” planar motor, the coil array moves with respect to a positionally fixed magnet array. In one embodiment, as disclosed in U.S. Patent No. 6,097,114 to Hazelton and shown schematically in **Fig. 1**, a moving coil planar motor **100** includes a base **102** with a flat magnet array **103** having a plurality of magnets **104**. A single X coil **106** and two Y Coils **108, 110** are attached to the underside of a stage frame **112** (drawn in dashed lines) suspended above and parallel to magnet array **102**. Y coils **108, 110** are similar in structure to one another and have coil wires oriented to provide force substantially in a Y direction. X coil **106** and Y coils **108, 110** are similar in structure, but X coil **106** has coil wires oriented to provide force substantially in an X direction 30 35 perpendicular to the Y direction.

X coil 106 and Y coils 108, 110 permit movement of stage frame 112. To provide force to stage frame 112 in the X direction relative to magnet array 102, two phase, three phase, or multiphase commutated electric current is supplied to X coil 106 in a conventional manner by a commutation circuit and current source 114. To provide force to stage frame 112 in the Y direction, two phase, three phase, or multiphase commutated electric current is supplied to either one or both of the Y coils 108, 110 in a conventional manner by respective commutation circuits and current sources 116 and/or 118. To provide rotational torque to frame 112 relative to magnet array 102 in a horizontal plane parallel to the X and Y axes, commutated electric current is supplied to either of Y coils 108, 110 individually by respective commutation circuits and current source 116 or 118. Alternatively, electric current is supplied to both Y coils 108, 110 simultaneously but with opposite polarities by respective commutation circuits and current sources 116, 118, providing Y force to one of Y coils 108, 110 in one direction and the other Y coil 108, 110 in an opposite direction, thereby generating a torque about an axis normal to the XY plane. This torque typically causes rotation of stage frame 112 in the XY plane.

In a second design, also disclosed in U.S. Patent No. 6,097,114 to Hazelton and shown schematically in Fig. 2, a “moving magnet type” planar motor includes a magnet array that moves with respect to a positionally fixed coil array. In one embodiment, moving magnet planar motor 200 includes an upper surface of a flat base 202 that is covered with coil units 204. A positioning stage 206 is suspended above flat base 202 and has an array of magnets 208 facing the upper surface of flat base 202. A conventional commutation circuit (not shown) controls and supplies electric current to coil units 204 in accordance with the desired direction of travel of positioning stage 206. Appropriately commutated electric current creates Lorentz forces, which propel positioning stage 206 to a desired location, altitude, and attitude.

Suspension of a stage 112, 206 may be accomplished using a variety of techniques. For example, additional, permanent magnets may be provided on the upper surface of a stage 112, 206 and on a stationary frame located above the stage 112, 206 (not shown). Alternatively, an air bearing may be provided between a stage 112, 206 and its respective base 102, 202. Electromagnetic force generated by the motor may instead provide the necessary suspension force.

Despite these developments, there is a need for a planar motor control that simultaneously controls translational forces in the X- and Y- directions and θ_z rotational movement. In addition, in order to achieve smooth operation of planar motors, rigorous computational power must be provided. For example, complex mathematical relationships

must be evaluated to achieve the desired torque and translation in the X and Y directions. To this end, significant CPU power typically is required. A need exists, therefore, for planar motor control using relationships with less complexity.

Also, there is a need for a planar motor control that permits torque control
5 with very low force ripple.

SUMMARY OF THE INVENTION

The present invention is related to a planar motor including a coil array having a plurality of coils, each coil fixed in position with respect to the other coils, and a magnet array having a plurality of magnets, each magnet fixed in position with respect to the other magnets, with the magnet array being movable above the coil array in at least two degrees of translational freedom and at least one degree of rotational freedom. The planar motor further includes a model-based predictive torque controller including a nonlinear current switching model, with the torque controller configured to provide current to
10 energize each coil in response to the position of each magnet with respect to a coil. The torque controller provides currents to the coil array to at least substantially reduce force
15 ripple during movement of the magnet array.

The torque controller may simultaneously stabilize translational and rotational movement, and may compensate for torque produced by translation. The coil
20 array may be square., and may include at least 25 coils.

The present invention also is related to a method for controlling a planar motor for movement in three degrees of freedom. The method includes: positioning a movable magnet array over a fixed coil array, the coil array having coils generally disposed in a plane defining first and second directions that are substantially orthogonal to one
25 another, and the magnet array having magnets with magnetic fields; applying currents to the coils following a nonlinear current switching model to control movement of the magnet array and substantially reduce force ripple during the movement. The method may further include determining a first translational force for the magnet array in the first direction and a second translational force for the magnet array in the second direction. In addition, the
30 method may include determining a torque for the magnet array in a third direction perpendicular to the first and second directions.

The present invention further is related to a planar motor including magnet array means, coil array means, and control means providing electric current to the coil array means for controlled movement of the magnet array means in three degrees of freedom

including non-linear current switching means for at least substantially reducing force ripple during movement of the magnet array.

The present invention also is related to a stage system including a planar motor. The planar motor includes: a coil array having a plurality of coils, each coil fixed in position with respect to the other coils; a magnet array having a plurality of magnets, each magnet fixed in position with respect to the other magnets, the magnet array being movable above the coil array in at least two degrees of translational freedom and at least one degree of rotational freedom; and a model-based predictive torque controller comprising a nonlinear current switching model, the torque controller configured to provide current to energize each coil in response to the position of each magnet with respect to a coil. The torque controller provides currents to the coil array to at least substantially reduce force ripple during movement of the magnet array.

Furthermore, the present invention is related to an exposure apparatus including an illumination system that supplies radiant energy and a stage system including a planar motor. The planar motor includes: a coil array having a plurality of coils, each coil fixed in position with respect to the other coils; a magnet array having a plurality of magnets, each magnet fixed in position with respect to the other magnets, the magnet array being movable above the coil array in at least two degrees of translational freedom and at least one degree of rotational freedom; and a model-based predictive torque controller comprising a nonlinear current switching model, the torque controller configured to provide current to energize each coil in response to the position of each magnet with respect to a coil. The torque controller provides currents to the coil array to at least substantially reduce force ripple during movement of the magnet array, and the stage system carries at least one object disposed on a path of the radiant energy. A device can be manufactured with the exposure apparatus. Any of a variety of devices such as semiconductor chips (e.g., integrated circuits or large-scale integrations), liquid crystal panels, CCDs, thin film magnetic heads, or micro-machines, can be manufactured with the exposure apparatus.

The present invention additionally is related to a wafer including an image, wherein the image is formed with an exposure apparatus that includes an illumination system that supplies radiant energy and a stage system that includes a planar motor. The planar motor includes: a coil array having a plurality of coils, each coil fixed in position with respect to the other coils; a magnet array having a plurality of magnets, each magnet fixed in position with respect to the other magnets, the magnet array being movable above the coil array in at least two degrees of translational freedom and at least one degree of rotational freedom; and a model-based predictive torque controller comprising a nonlinear

current switching model, the torque controller configured to provide current to energize each coil in response to the position of each magnet with respect to a coil. The torque controller provides currents to the coil array to at least substantially reduce force ripple during movement of the magnet array, and the stage system carries at least one object
5 disposed on a path of the radiant energy.

BRIEF DESCRIPTION OF THE DRAWINGS

Preferred features of the present invention are disclosed in the accompanying drawings, wherein similar reference characters denote similar elements throughout the
10 several views, and wherein:

Fig. 1 is a perspective view schematically showing a prior art moving coil planar motor;

Fig. 2 is a perspective view schematically showing a prior art moving magnet planar motor;

15 Fig. 3 is a perspective view showing a moving magnet planar motor according to an embodiment of the present invention disposed at an initial position with respect to the coil array;

Fig. 4 is a plan view of the magnet array of Fig. 3;

20 Fig. 5 is a plan view of the magnet array of Fig. 3 disposed above a coil array, forming a planar motor;

Fig. 6 is a graph showing the magnet force constant of the planar motor of Fig. 5;

25 Fig. 6A is a graphical representation of a moving magnet force constant coefficient;

Fig. 6B is a graphical representation of the Im_x component of the magnetic force constant;

Fig. 6C is a graphical representation of the Im_y component of the magnetic force constant;

30 Fig. 7 is a partial plan view of the planar motor of Fig. 5 with one row of magnets and one row of coils;

Fig. 8 is a plan view of the magnet array of Fig. 3 disposed at another position with respect to the coil array;

Fig. 9 is an exemplar graph showing undesired torque behavior;

Fig. 9A is an exemplar graph related to torque compensation;

35 Fig. 9B is another exemplar graph related to torque compensation;

Fig. 10 is an exemplar graph showing torque compensation according to the present invention;

Fig. 11 is an exemplar graph showing translation compensation according to the present invention;

5 Fig. 12 is a block diagram of a position control system using an exemplary array of thirty-six coils in accordance with the present invention;

Fig. 13 is an elevational view, partially in section, showing a microlithographic apparatus in accordance with the present invention;

10 Fig. 14 is a flowchart showing the fabrication of semiconductor devices; and Fig. 15 is a flowchart showing details of the wafer processing step of Fig. 14.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring initially to **Fig. 3**, there is shown a perspective view of a moving magnet embodiment of a planar motor **300** including such a square flat planar coil array **302**. Moving magnet planar motors suitable for the present invention are disclosed, for example, in U.S. Patent No. 6,097,114 to Hazelton, U.S. Patent No. 6,114,781 to Hazelton *et al.*, and U.S. Patent No. 6,188,147 B1 to Hazelton *et al.*, the contents of which are hereby incorporated by reference in their entirety. A magnet array **304** is attached to a moving portion of a positioning stage **306**. Coils **308** of coil array **302** are attached to a fixed platen **310**. In this embodiment, magnet array **304** is sized such that four groups of coils **308** (16 coils) fit underneath magnet array **304**. Coils **308** can be switched electrically such that only the coils that are underneath magnet array **304** for producing force are energized. The other coils are switched off to minimize heating of the system. Magnet array **304** is configured to provide a magnetic flux field that interacts with coil array **302** to produce forces to move positioning stage **306** in three degrees of freedom (conventionally designated X, Y, θ_z) above coil array **302**. Although not shown in **Fig. 3**, air bearings and associated smooth, hard surfaces may be provided to facilitate movement of magnet array **304** with respect to coil array **302**.

As shown in the plan view of **Fig. 4**, in the preferred embodiment, magnet array **304** includes centrally-located, full-sized square magnets **312**, peripherally-located half magnets **314**, and quarter magnets **316** at the four corners. Half magnets **314** generate substantially one-half of the magnetic flux of full-sized magnets **312**, while quarter magnets **316** generate substantially one-quarter of said flux. The half magnets **314** and quarter magnets **316** provide efficient magnetic flux coupling with full-sized magnets **312**. Magnet array **304** is disposed about a center of gravity or origin **318**, and magnets **312**, **314**, **316**

form rows in the X direction and columns in the Y direction as defined by X and Y coordinate axes. Using these axes, the magnetic pitch of the array is defined as one-half the distance along a particular axis between centers of adjacent full-sized magnets 312. Each full-sized magnet 312 has a length of about 1 pitch, p , and an area of about one pitch squared (p^2), as shown graphically.

Turning to **Fig. 5**, magnet array 304 is disposed above coils 308 which are arranged in the current embodiment in a 6×6 square array. Six coils are in each column C_0 , C_1 , C_2 , C_3 , C_4 , C_5 and six coils are in each row R_0 , R_1 , R_2 , R_3 , R_4 , R_5 , thus forming an array of thirty-six coils 308. As will be described shortly, the combination of magnet array 304 and an array of coils 308 permits planar motor control in 3 degrees of freedom - x- and y- translation and z- rotation. Each coil 308 has a length of about 3 pitch, $3p$, and an area of about $9p^2$, as shown graphically. Persons of ordinary skill in the art will appreciate that the present invention may be readily adapted to control magnet arrays of different dimensions based on the teachings set forth herein. Preferably, a 5×5 or larger array of coils 308 is used, and the size of the coil array is selected in part based on the desired travel range for magnet array 304. In other embodiments, the numbers of rows and columns in a magnet array may be substantially larger and/or the number of rows and the number of columns may be unequal.

Fig. 6 shows the magnet force constant, K_m , for magnet array 304 of planar motor 300. In order to create X- and Y- translation forces, according to the Lorentz law, the two dimensional magnetic force constant, K_m , may be mathematically derived for a 2-dimensional planar motor. The moving magnet force constant coefficient curve is shown in **Fig. 6A**. As can be seen from **Fig. 6A**, the force constant magnitude has a trapezoid shape in both the x- and y-directions. The force constant coefficient curve may be used to derive equations for the x- and y- magnetic force constant. Referring to **Fig. 6A**, the moving magnet force constant amplitude, A , in x-movement with respect to portion A_1 (corresponding to $\text{Im } x$) is as follows:

$$A_{xx}(x_1, y_1) := \begin{cases} a \leftarrow 1.0 & \text{if } 0 \leq |x_1| < 4.5 \\ a \leftarrow -1 \cdot \frac{1}{3} \cdot |x_1| + 2.5 & \text{if } 4.5 \leq |x_1| < 7.5 \\ a \leftarrow 0 & \text{if } 7.5 \leq |x_1| \end{cases}; \quad (1)$$

$$5 \quad A_{xy}(x_1, y_1) := \begin{cases} a \leftarrow 1.0 & \text{if } 0 \leq |y_1| < 4.5 \\ a \leftarrow -0.5 \cdot |y_1| + 3.25 & \text{if } 4.5 \leq |y_1| < 5.5 \\ a \leftarrow 0.5 & \text{if } 5.5 \leq |y_1| < 6.5 \\ a \leftarrow -0.5 \cdot |y_1| + 3.75 & \text{if } 6.5 \leq |y_1| < 7.5 \\ a \leftarrow 0 & \text{if } 7.5 \leq |y_1| \end{cases}; \quad (2)$$

$$10 \quad A_x(x_1, y_1) := A_{xx}(x_1, y_1) \cdot A_{xy}(x_1, y_1) \cdot k_x. \quad (3)$$

Further, with respect to portion A₂ the moving magnet force constant amplitude, A_x is as follows with respect to y-movement:

$$15 \quad A_{yx}(x_1, y_1) := \begin{cases} a \leftarrow -0.5 \cdot |x_1| & \text{if } 0 \leq |x_1| < 4.5 \\ a \leftarrow -0.5 \cdot |x_1| + 3.25 & \text{if } 4.5 \leq |x_1| < 5.5 \\ a \leftarrow 0.5 & \text{if } 5.5 \leq |x_1| < 6.5 \\ a \leftarrow -0.5 \cdot |x_1| + 3.75 & \text{if } 6.5 \leq |x_1| < 7.5 \\ a \leftarrow 0 & \text{if } 7.5 \leq |x_1| \end{cases}; \quad (4)$$

$$20 \quad A_{yy}(x_1, y_1) := \begin{cases} a \leftarrow 1.0 & \text{if } 0 \leq |y_1| < 4.5 \\ a \leftarrow -1 \cdot \frac{1}{3} \cdot |y_1| + 2.5 & \text{if } 4.5 \leq |y_1| < 7.5 \\ a \leftarrow 0 & \text{if } 7.5 \leq |y_1| \end{cases}; \quad (5)$$

$$A_y(x_1, y_1) := A_{yx}(x_1, y_1) \cdot A_{yy}(x_1, y_1) \cdot k_y. \quad (6)$$

25 **Figs. 6B and 6C** show graphical representations of the Im x and Im y components, respectively, of the magnetic force constant, where coordinates (42, 42) are equivalent to position (0,0) at the intersection of the x- and y- axes in **Fig. 5**.

Referring again to **Fig. 5**, the magnet force constant for a given row of coils may be determined. For example, with the origin used for (x₁, y₁), the coils at positions (R₂,

$$30 \quad k_{ma}(x_1, y_1) := \begin{bmatrix} A_x(-x_1 - 6, -y_1) \cdot P_1 & A_x(-x_1 - 3, -y_1) \cdot P_2 & A_x(-x_1 - 0, -y_1) \cdot P_3 \\ A_y(-x_1 - 6, -y_1) \cdot P_4 & A_y(-x_1 - 3, -y_1) \cdot P_5 & A_y(-x_1 - 0, -y_1) \cdot P_6 \\ 0 & 0 & 0 \end{bmatrix} \quad (7)$$

35 C₀), (R₂, C₁), and (R₂, C₂) contribute the following to the magnetic force constant: where

$$P_1 = \sin(-x_1 \cdot \frac{\pi}{2} - 6 \cdot \frac{\pi}{2}) \cdot \cos(-y_1 \cdot \frac{\pi}{2}); \quad P_2 = \sin(-x_1 \cdot \frac{\pi}{2} - 3 \cdot \frac{\pi}{2}) \cdot \cos(-y_1 \cdot \frac{\pi}{2}); \quad (8)$$

$$P_3 = \sin(-x_1 \cdot \frac{\pi}{2} - 0 \cdot \frac{\pi}{2}) \cdot \cos(-y_1 \cdot \frac{\pi}{2});$$

and

$$P_4 = \cos(-x_1 \cdot \frac{\pi}{2} - 6 \cdot \frac{\pi}{2}) \cdot \sin(-y_1 \cdot \frac{\pi}{2}); \quad P_5 = \cos(-x_1 \cdot \frac{\pi}{2} - 3 \cdot \frac{\pi}{2}) \cdot \sin(-y_1 \cdot \frac{\pi}{2}); \quad (9)$$

$$P_6 = \cos(-x_1 \cdot \frac{\pi}{2} - 0 \cdot \frac{\pi}{2}) \cdot \sin(-y_1 \cdot \frac{\pi}{2}).$$

Similarly, the coils at positions (R₂, C₃), (R₂, C₄), and (R₂, C₅) contribute the following to the magnetic force constant:

$$k_{mb}(x_1, y_1) := \begin{bmatrix} A_x(-x_1 + 3, y_1) \cdot P_7 & A_x(-x_1 + 6, y_1) \cdot P_8 & A_x(-x_1 + 9, y_1) \cdot P_9 \\ A_y(-x_1 + 3, y_1) \cdot P_{10} & A_x(-x_1 + 6, y_1) \cdot P_{11} & A_x(-x_1 + 9, y_1) \cdot P_{12} \\ 0 & 0 & 0 \end{bmatrix} \quad (10)$$

where

$$P_7 = \sin(-x_1 \cdot \frac{\pi}{2} + 3 \cdot \frac{\pi}{2}) \cdot \cos(-y_1 \cdot \frac{\pi}{2}); \quad P_8 = \sin(-x_1 \cdot \frac{\pi}{2} + 6 \cdot \frac{\pi}{2}) \cdot \cos(-y_1 \cdot \frac{\pi}{2}); \quad (11)$$

$$P_9 = \sin(-x_1 \cdot \frac{\pi}{2} + 9 \cdot \frac{\pi}{2}) \cdot \cos(-y_1 \cdot \frac{\pi}{2});$$

and

$$P_{10} = \cos(-x_1 \cdot \frac{\pi}{2} + 3 \cdot \frac{\pi}{2}) \cdot \sin(-y_1 \cdot \frac{\pi}{2}); \quad P_{11} = \cos(-x_1 \cdot \frac{\pi}{2} + 6 \cdot \frac{\pi}{2}) \cdot \sin(-y_1 \cdot \frac{\pi}{2}); \quad (12)$$

$$P_{12} = \cos(-x_1 \cdot \frac{\pi}{2} + 9 \cdot \frac{\pi}{2}) \cdot \sin(-y_1 \cdot \frac{\pi}{2}).$$

With reference to Fig. 7, row R₂ of coils 308 is shown with magnets 312, 314 of magnet array 304 positioned thereabout. Magnets 312, 314 span a total distance D₁ along the X-axis, which length is equal to the length spanned by four complete coils 308. Thus, preferably, at least five coils 308 are provided in each row so that magnets 312, 314 may be translated with respect to coils 308. In addition, in the preferred embodiment, distance D₁ is about 430 mm. The array of magnets disposed along the X-axis includes five full-sized magnets 312 and two half magnets 314, which is numerically equivalent to six full-sized magnets 312 each having an area of about one pitch squared (p²). Also, extending between half magnets 314 along the X-axis, open square non-magnet portions 320 use the equivalent area of six full-sized magnets 312, and so the magnet array uses the total equivalent area of twelve full-sized magnets 312. The preferred embodiment has a pitch, therefore, of the ratio of D₁ to 12, or 430/12 mm. Notably, in the embodiment of planar motor 304 discussed herein, magnets 312, 314 along the X-axis alternate in North (N) - South (S) polarity. Each change in unit pitch also is equal to a 90° phase difference as

encountered with sine or cosine functions; while magnet 312 at origin 318 is described as having an N-polarity and being at 0° , adjacent magnets with an S-polarity have a 180° phase difference.

The combination of row **R**₂ of coils **308** and magnets **312**, **314** of magnet array **304** produces a translational force along the X-axis. To create a four-phase linear motor, the magnet force constants, K_m , located above each coil **308** are determined. The force constant of magnet **312** located above coil **308** in column **C**₂, which coincides with commutation origin **318**, is constructed as follows:

$$K_{x_{\max(0)}} = K_a \sin(x + 0) \quad (13)$$

Thus, K_a is the peak-to-peak amplitude of the magnet force constant, K_m . Similarly, the force constants of magnets 312 located above coils 308 in columns C_3, C_2 , respectively, are as follows:

$$K_{x_{mag(3)}} = K_a \sin(x + 3\frac{\pi}{2}) \quad (14)$$

$$K_{x_{\max(-3)}} = K_a \sin(x - 3\frac{\pi}{2}) \quad (15)$$

It should be noted that the factors of 3 in Eqs. 14 and 15 above are due to the offset of the
 25 respective coils a distance of 3 pitch from origin 318. Finally, the force constants of
 magnets 314 located above coils 308 in columns C_4 , C_6 , respectively, are as follows:

$$K_{x_{\max(-6)}} = \frac{1}{2} K_a \sin(x - 6\frac{\pi}{2}); \quad (16)$$

$$30 \quad K_{x_{mag(6)}} = \frac{1}{2} K_a \sin(x + 6\frac{\pi}{2}). \quad (17)$$

As indicated in Eqs. 16 and 17, the factors of 6 are due to the offset of the respective coils a distance of 6 pitch from origin 318, while the factors of $\frac{1}{2}$ account for the half-size of magnets 314.

Next, to create a driving force in the X-direction and located at the center of each coil 308, assuming the current in each coil 308 has the same phase as the respective magnet force constant, the following currents are required for coils 308 in columns **C**₁, **C**₂, **C**₃, **C**₄, **C**₅:

5

$$I_{x(-6)} = I \sin\left(x - 6\frac{\pi}{2}\right); \quad (18)$$

$$I_{x(-3)} = I \sin\left(x - 3\frac{\pi}{2}\right); \quad (19)$$

$$I_{x(0)} = I \sin\left(x + 0\frac{\pi}{2}\right); \quad (20)$$

10

$$I_{x(3)} = I \sin\left(x + 3\frac{\pi}{2}\right); \quad (21)$$

$$I_{x(6)} = I \sin\left(x + 6\frac{\pi}{2}\right); \quad (22)$$

Thus, a total driving force, F, is the summation of the products of the individual driving forces and their respective force constants:

$$F = \frac{1}{2} I_{x(-6)} K_{x_{mag}(-6)} + I_{x(-3)} K_{x_{mag}(-3)} + I_{x(0)} K_{x_{mag}(0)} + \quad (23)$$

$$I_{x(3)} K_{x_{mag}(3)} + \frac{1}{2} I_{x(6)} K_{x_{mag}(6)}$$

20

Equation 24 may be simplified with the following relations.

$$\frac{1}{2} I_{x(-6)} K_{x_{mag}(-6)} = \frac{1}{2} I_{x(6)} K_{x_{mag}(6)} = \frac{1}{2} IK_a \sin^2(x); \quad (24)$$

$$I_{x(-3)} K_{x_{mag}(-3)} = I_{x(3)} K_{x_{mag}(3)} = IK_a \cos^2(x); \quad (25)$$

25

$$I_{x(0)} K_{x_{mag}(0)} = IK_a \sin^2(x). \quad (26)$$

And upon simplification, the total force generated at row **R**₂ becomes:

$$F = 2IK_a [\sin^2(x) + \cos^2(x)] = 2IK_a \quad (27)$$

30

Equation 27 may be further extended, so that the force generated at row **R**₂ by coils 308 at locations (0,0), (3,0), (6,0), (-6,0), and (-3,0) is described as:

35

Row 2: (28)

$$\begin{aligned}
 F_x = & K_x \sin(x+0) \cos(y) [I_x \sin(x+0) \cos(y) + I_y \sin(y) \cos(x+0)] + \\
 & K_x \sin(x+90) \cos(y) [I_x \sin(x+90) \cos(y) + I_y \sin(y) \cos(x+90)] + \\
 5 & \frac{1}{2} K_x \sin(x+180) \cos(y) [I_x \sin(x+180) \cos(y) + I_y \sin(y) \cos(x+180)] + \\
 & \frac{1}{2} K_x \sin(x+180) \cos(y) [I_x \sin(x+180) \cos(y) + I_y \sin(y) \cos(x+180)] + \\
 & K_x \sin(x+270) \cos(y) [I_x \sin(x+270) \cos(y) + I_y \sin(y) \cos(x+270)] \\
 = & 2I_x K_a \cos^2(y)
 \end{aligned}$$

10

As will be described shortly, if all coils 308 in rows **R₀**, **R₁**, **R₂**, **R₃**, **R₄**, **R₅** are used to create a translational force in the X-direction, the equation for calculating the force simplifies to:

$$15 \quad F_x = 4I_x K_a \quad (29)$$

Similarly, the driving force in the Y-direction at column **C₂** created by coils 308 at locations (0,0), (0,3), (0,6), (0,-6), and (0,-3) is described as:

Column 2: (30)

$$\begin{aligned}
 20 \quad F_y = & K_y \sin(y+0) \cos(x) [I_x \sin(x+0) \cos(y) + I_y \sin(y) \cos(x+0)] + \\
 & K_y \sin(y+90) \cos(x) [I_x \sin(x+90) \cos(y) + I_y \sin(y+90) \cos(x)] + \\
 & \frac{1}{2} K_y \sin(y+180) \cos(x) [I_x \sin(x+180) \cos(y) + I_y \sin(y+180) \cos(x)] + \\
 & \frac{1}{2} K_y \sin(y+180) \cos(x) [I_x \sin(x+180) \cos(y) + I_y \sin(y+180) \cos(x)] + \\
 25 \quad & K_y \sin(y+270) \cos(x) [I_x \sin(x+270) \cos(y) + I_y \sin(y+270) \cos(x)] \\
 = & 2I_y K_a \cos^2(x)
 \end{aligned}$$

Accounting for the force contributed by all of coils 308 in columns **C₀**, **C₁**, **C₂**, **C₃**, **C₄**, **C₅**, the total translational force in the Y-direction simplifies to:

$$30 \quad F_y = 4I_y K_a \quad (31)$$

It is desirable to provide torque or yaw control (θ_z) for the moving magnet planar motor so that control of a third degree of freedom complements the X- and Y-direction translational force control already discussed. In order to calculate torque, the 35 distance from each of the coils to the center of gravity of the coil array must be known. To

this end, referring again to **Fig. 5**, it is noted that the distances between each of coils 308 are fixed. Thus, as shown in **Fig. 5**, the center points **CEN** of coils 308 in rows **R₀** and **R₄** are offset in the y-direction by distances **L₀**, **L₄**, respectively, from the x-axis that extends through origin 318, the center points **CEN** of coils 308 in rows **R₁** and **R₃** are offset by 5 distances **L₁**, **L₃**, respectively, and the center points **CEN** of coils 308 in row **R₂** are offset by a distance **L₂** from the X-axis, which is zero. Rows **R₀** and **R₄** each produce one-half of the force produced by each of rows **R₁**, **R₂**, **R₃**, because of the difference in size of the magnets in the rows. At the position shown in **Fig. 5**, magnet array 304 is disposed only above rows **R₀**, **R₁**, **R₂**, **R₃**, **R₄**, so that the total translation forces made by coils 308 in each 10 of these rows is as follows:

$$F_{\text{row } 0} = \frac{2I_u K_a \cos^2(y)}{2}; \quad (32)$$

$$F_{\text{row } 1} = 2I_u K_a \sin^2(y); \quad (33)$$

$$F_{\text{row } 2} = 2(I_u + I_l)K_a \cos^2(y); \quad (34)$$

$$F_{\text{row } 3} = 2I_l K_a \sin^2(y); \quad (35)$$

$$F_{\text{row } 4} = \frac{2I_l K_a \cos^2(y)}{2}. \quad (36)$$

where “upper” rows **R₀**, **R₁**, **R₂** each have a current amplitude of **I_u** amps, and “lower” rows 20 **R₃**, **R₄** each have a current amplitude of **I_l** amps.

The torque equation thus is derived as follows:

$$T_{\text{row}(y)} = \frac{1}{2}L_0(2)I_u K_a \cos^2(y) + L_1(2)I_u K_a \sin^2(y) + L_2(2)(I_u + I_l)K_a \cos^2(y) - L_3(2)I_l K_a \sin^2(y) - \frac{1}{2}L_4(2)I_l K_a \cos^2(y) \quad (37)$$

The current used to generate the torque is defined such that **I_u=-I_l**, thus eliminating the third term of Eq. 37 which then further simplifies to the following:

$$\begin{aligned} T_{\text{row}(y)} &= \frac{1}{2}L_0(2)I_u K_a \cos^2(y) + L_1(2)I_u K_a \sin^2(y) \\ 30 &\quad - L_3(2)I_l K_a \sin^2(y) - \frac{1}{2}L_4(2)I_l K_a \cos^2(y) \\ &= (L_0 + L_4)I_u K_a \cos^2(y) + (L_1 + L_3)(2)I_u K_a \sin^2(y) \end{aligned} \quad (38)$$

The offset distances **L₀**, **L₁**, **L₂**, **L₃**, **L₄** are fixed, and in the preferred embodiment, the value of (**L₀+L₄**) is fixed at 12 pitches while the value of (**L₁+L₃**) is fixed at 6 pitches. 35 Equation 38 may be further simplified as:

$$\begin{aligned} T_{\text{row}(y)} &= 12I_u K_a [\sin^2(y) + \cos^2(y)] \\ &= 12K_a I_{u(\text{row})} \end{aligned} \quad (39)$$

The θ_z torque thus may be created by a row of coils 308. In addition, a column of coils 308
5 also may produce the θ_z torque, which is similarly determined to be as follows:

$$T_{\text{column}(x)} = 12K_a I_{u(\text{column})} \quad (40)$$

Moreover, both a row and column of coils 308 may be used to produce the θ_z torque with
one-half the desired torque produced by each of the column and row.

10 In order to generate torque, the amplitude of the current supplied to a coil
308 is as follows:

$$I_x = \frac{F_x}{4K_a}; \quad (41)$$

$$15 \quad I_y = \frac{F_y}{4K_a}. \quad (42)$$

The current for a row and column of coils is found to be as follows:

$$20 \quad I_{u(\text{row})} = \frac{T_{\text{row}(y)}}{12K_a}; \quad (43)$$

$$I_{u(\text{column})} = \frac{T_{\text{column}(x)}}{12K_a}. \quad (44)$$

With the above equations, the amplitude of the coil current may be determined as a function
25 of the desired translational force and torque.

Equations 32 to 44 can be applied with both the X- and Y-axial positions
varying between about -0.5 pitch and about +0.5 pitch. This application constraint,
however, places a significant restriction on the available planar motor moving area. To
extend the area of movement, a switching function is used for coil row energization, as
30 follows:

$$\begin{aligned}
I_{tzx_0} &\leftarrow -\frac{T_{z_1}}{6k_y \cdot 2} & \text{if } -1.5 \leq y_1 \leq 2.0 \\
I_{tzx_0} &\leftarrow 0 & \text{otherwise} \\
I_{tzx_1} &\leftarrow -\frac{T_{z_1}}{6k_y \cdot 2} & \text{if } -1.5 \leq y_1 \leq 4.0 \\
I_{tzx_1} &\leftarrow 0 & \text{otherwise} \\
I_{tzx_2} &\leftarrow -\frac{T_{z_1}}{6k_y \cdot 2} & \text{if } -1.5 \leq y_1 \leq 1.0 \\
I_{tzx_2} &\leftarrow -\frac{T_{z_1}}{6k_y \cdot 2} & \text{if } 1.0 \leq y_1 \leq 4.5 \\
I_{tzx_2} &\leftarrow 0 & \text{otherwise} \\
I_{tzx_3} &\leftarrow -\frac{T_{z_1}}{6k_y \cdot 2} & \text{if } -1.5 \leq y_1 \leq 2.0 \\
I_{tzx_3} &\leftarrow -\frac{T_{z_1}}{6k_y \cdot 2} & \text{if } 4.0 \leq y_1 \leq 4.5 \\
I_{tzx_3} &\leftarrow 0 & \text{otherwise} \\
I_{tzx_4} &\leftarrow -\frac{T_{z_1}}{6k_y \cdot 2} & \text{if } -1.0 \leq y_1 \leq 4.5 \\
I_{tzx_4} &\leftarrow 0 & \text{otherwise} \\
I_{tzx_5} &\leftarrow -\frac{T_{z_1}}{6k_y \cdot 2} & \text{if } 1.0 \leq y_1 \leq 4.5 \\
I_{tzx_5} &\leftarrow 0 & \text{otherwise} \\
I_{tzx} &\leftarrow \frac{I_{tzx}}{2}
\end{aligned} \tag{45}$$

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A switching function for coil column energization is as follows:

$$\begin{aligned}
 & I_{tzy_0} \leftarrow -\frac{T_{z1}}{6k_x^2} \quad \text{if } -1.5 \leq x_1 \leq 2.0 \\
 & I_{tzy_0} \leftarrow 0 \quad \text{otherwise} \\
 5 & I_{tzy_1} \leftarrow -\frac{T_{z1}}{6k_x^2} \quad \text{if } -1.5 \leq x_1 \leq 4.0 \\
 & I_{tzy_1} \leftarrow 0 \quad \text{otherwise} \\
 & I_{tzy_2} \leftarrow -\frac{T_{z1}}{6k_x^2} \quad \text{if } -1.5 \leq x_1 \leq 1.0 \\
 & I_{tzy_2} \leftarrow -\frac{T_{z1}}{6k_x^2} \quad \text{if } 1.0 \leq x_1 \leq 4.5 \\
 & I_{tzy_2} \leftarrow 0 \quad \text{otherwise} \\
 10 & I_{tzy_3} \leftarrow -\frac{T_{z1}}{6k_x^2} \quad \text{if } -1.5 \leq x_1 \leq 2.0 \quad (46) \\
 & I_{tzy_3} \leftarrow -\frac{T_{z1}}{6k_x^2} \quad \text{if } 4.0 \leq x_1 \leq 4.5 \\
 & I_{tzy_3} \leftarrow 0 \quad \text{otherwise} \\
 & I_{tzy_4} \leftarrow -\frac{T_{z1}}{6k_x^2} \quad \text{if } -1.0 \leq x_1 \leq 4.5 \\
 & I_{tzy_4} \leftarrow 0 \quad \text{otherwise} \\
 15 & I_{tzy_5} \leftarrow -\frac{T_{z1}}{6k_x^2} \quad \text{if } 1.0 \leq x_1 \leq 4.5 \\
 & I_{tzy_5} \leftarrow 0 \quad \text{otherwise} \\
 & I_{tzy} \leftarrow \frac{I_{tzy}}{2}
 \end{aligned}$$

- 20 For example, the switching function of Eq. 45 is applied as follows. To create desired torque over the entire planar motor moving area, a row \mathbf{R}_0 activation function is used. When magnet array 304 is located between -1.5 pitch and 2.0 pitch, row \mathbf{R}_0 torque control current is energized; otherwise, row \mathbf{R}_0 torque control current is turned off. Similarly, row \mathbf{R}_1 coils are energized when magnet array 304 is located between about -1.5 pitch to about 25 4.0 pitch; otherwise, row \mathbf{R}_1 coils are turned off. In the preferred embodiment, the switching function of Eq. 45 allows the desired torque to be generated with magnet array 304 at a wide range of locations.

The simultaneous generation of X- and Y- translational movement and θ_z rotational movement is governed by the following equations, in which the magnet force 30 constant is multiplied by the sum of the commutation functions for translational force and torque, for each row of coils 308:

(47)

For row 2:

$$\begin{aligned}
 F_x &= K_x \sin(x+0) \cos(y) \left[\begin{array}{l} (I_x + I_{t(r2)}) \sin(x+0) \cos(y) + \\ (I_{y(c2)} + I_{t(c2)}) \sin(y) \cos(x) \end{array} \right] + \\
 5 &\quad K_x \sin(x+90) \cos(y) \left[\begin{array}{l} (I_x + I_{t(r2)}) \sin(x+90) \cos(y) + \\ (I_{y(c1)} + I_{t(c1)}) \sin(y) \cos(x+90) \end{array} \right] + \\
 &\quad \frac{1}{2} K_x \sin(x+180) \cos(y) \left[\begin{array}{l} (I_x + I_{t(r2)}) \sin(x+180) \cos(y) + \\ (I_{y(c0)} + I_{t(c0)}) \sin(y) \cos(x+180) \end{array} \right] + \\
 10 &\quad \frac{1}{2} K_x \sin(x+0) \cos(y) \left[\begin{array}{l} (I_x + I_{t(r2)}) \sin(x+0) \cos(y) + \\ (I_{y(c4)} + I_{t(c4)}) \sin(y) \cos(x) \end{array} \right] + \\
 &\quad K_x \sin(x+270) \cos(y) \left[\begin{array}{l} (I_x + I_{t(r2)}) \sin(x+270) \cos(y) + \\ (I_{y(c3)} + I_{t(c3)}) \sin(y) \cos(x+270) \end{array} \right] \\
 15 &= 2(I_x + I_{t(r2)}) K_a \cos^2(y) \\
 &= 2I_x K_a \cos^2(y) + 2I_{t(r2)} K_a \cos^2(y)
 \end{aligned}$$

20

(48)

For row 1:

$$\begin{aligned}
 F_x &= K_x \sin(x+0) \cos(y+90) \left[\begin{array}{l} (I_x + I_{t(r1)}) \sin(x+0) \cos(y+90) + \\ (I_{y(c2)} + I_{t(c2)}) \sin(y+90) \cos(x) \end{array} \right] + \\
 25 &\quad K_x \sin(x+90) \cos(y+90) \left[\begin{array}{l} (I_x + I_{t(r1)}) \sin(x+90) \cos(y+90) + \\ (I_{y(c1)} + I_{t(c1)}) \sin(y+90) \cos(x+90) \end{array} \right] + \\
 &\quad \frac{1}{2} K_x \sin(x+180) \cos(y+90) \left[\begin{array}{l} (I_x + I_{t(r1)}) \sin(x+180) \cos(y+90) + \\ (I_{y(c0)} + I_{t(c0)}) \sin(y+90) \cos(x+180) \end{array} \right] + \\
 30 &\quad \frac{1}{2} K_x \sin(x+180) \cos(y+90) \left[\begin{array}{l} (I_x + I_{t(r1)}) \sin(x+180) \cos(y+90) + \\ (I_{y(c4)} + I_{t(c4)}) \sin(y+90) \cos(x+180) \end{array} \right] + \\
 &\quad K_x \sin(x+270) \cos(y+90) \left[\begin{array}{l} (I_x + I_{t(r1)}) \sin(x+270) \cos(y+90) + \\ (I_{y(c3)} + I_{t(c3)}) \sin(y+90) \cos(x+270) \end{array} \right] \\
 35 &= 2I_x K_a \sin^2(y) + 2I_{t(r1)} K_a \sin^2(y)
 \end{aligned}$$

(49)

For row 0:

$$\begin{aligned}
 F_x &= \frac{1}{2} K_x \sin(x+0) \cos(y+180) \left[\begin{array}{l} (I_x + I_{t(r0)}) \sin(x+0) \cos(y+180) \\ (I_{y(c2)} + I_{t(c2)}) \sin(y+180) \cos(x) \end{array} \right] + \\
 5 &\quad \frac{1}{2} K_x \sin(x+90) \cos(y+180) \left[\begin{array}{l} (I_x + I_{t(r0)}) \sin(x+90) \cos(y+180) \\ (I_{y(c1)} + I_{t(c1)}) \sin(y+180) \cos(x+90) \end{array} \right] + \\
 10 &\quad \frac{1}{4} K_x \sin(x+180) \cos(y+180) \left[\begin{array}{l} (I_x + I_{t(r0)}) \sin(x+180) \cos(y+180) \\ (I_{y(c0)} + I_{t(c0)}) \sin(y+180) \cos(x+180) \end{array} \right] + \\
 15 &\quad \frac{1}{4} K_x \sin(x+180) \cos(y+180) \left[\begin{array}{l} (I_x + I_{t(r0)}) \sin(x+180) \cos(y+180) \\ (I_{y(c4)} + I_{t(c4)}) \sin(y+180) \cos(x+180) \end{array} \right] + \\
 &\quad \frac{1}{2} K_x \sin(x+270) \cos(y+180) \left[\begin{array}{l} (I_x + I_{t(r0)}) \sin(x+270) \cos(y+180) \\ (I_{y(c3)} + I_{t(c3)}) \sin(y+180) \cos(x+270) \end{array} \right] \\
 &= 1I_x K_a \cos^2(y) + 1I_{t(r0)} K_a \cos^2(y)
 \end{aligned}$$

(50)

For row 3:

$$\begin{aligned}
 20 &F_x = K_x \sin(x+0) \cos(y+90) \left[\begin{array}{l} (I_x + I_{t(r3)}) \sin(x+0) \cos(y+90) \\ (I_{y(c2)} + I_{t(c2)}) \sin(y+90) \cos(x) \end{array} \right] + \\
 &\quad K_x \sin(x+90) \cos(y+90) \left[\begin{array}{l} (I_x + I_{t(r3)}) \sin(x+90) \cos(y+90) \\ (I_{y(c1)} + I_{t(c1)}) \sin(y+90) \cos(x+90) \end{array} \right] + \\
 25 &\quad \frac{1}{2} K_x \sin(x+180) \cos(y+90) \left[\begin{array}{l} (I_x + I_{t(r3)}) \sin(x+180) \cos(y+90) \\ (I_{y(c0)} + I_{t(c0)}) \sin(y+90) \cos(x+180) \end{array} \right] + \\
 &\quad \frac{1}{2} K_x \sin(x+180) \cos(y+90) \left[\begin{array}{l} (I_x + I_{t(r3)}) \sin(x+180) \cos(y+90) \\ (I_{y(c4)} + I_{t(c4)}) \sin(y+90) \cos(x+180) \end{array} \right] + \\
 30 &\quad K_x \sin(x+270) \cos(y+90) \left[\begin{array}{l} (I_x + I_{t(r3)}) \sin(x+270) \cos(y+90) \\ (I_{y(c3)} + I_{t(c3)}) \sin(y+90) \cos(x+270) \end{array} \right] \\
 &= 2I_x K_a \sin^2(y) + 2I_{t(r3)} K_a \sin^2(y)
 \end{aligned}$$

(51)

For row 4:

$$\begin{aligned}
 F_x &= \frac{1}{2} K_x \sin(x+0) \cos(y+180) \left[\begin{array}{l} (I_x + I_{t(r4)}) \sin(x+0) \cos(y+180) \\ (I_{y(c2)} + I_{t(c2)}) \sin(y+180) \cos(x) \end{array} \right] + \\
 5 &\quad \frac{1}{2} K_x \sin(x+90) \cos(y+180) \left[\begin{array}{l} (I_x + I_{t(r4)}) \sin(x+90) \cos(y+180) \\ (I_{y(c1)} + I_{t(c1)}) \sin(y+180) \cos(x+90) \end{array} \right] + \\
 10 &\quad \frac{1}{4} K_x \sin(x+180) \cos(y+180) \left[\begin{array}{l} (I_x + I_{t(r4)}) \sin(x+180) \cos(y+180) \\ (I_{y(c0)} + I_{t(c0)}) \sin(y+180) \cos(x+180) \end{array} \right] + \\
 15 &\quad \frac{1}{4} K_x \sin(x+180) \cos(y+180) \left[\begin{array}{l} (I_x + I_{t(r4)}) \sin(x+180) \cos(y+180) \\ (I_{y(c4)} + I_{t(c4)}) \sin(y+180) \cos(x+180) \end{array} \right] + \\
 &\quad \frac{1}{2} K_x \sin(x+270) \cos(y+180) \left[\begin{array}{l} (I_x + I_{t(r4)}) \sin(x+270) \cos(y+180) \\ (I_{y(c3)} + I_{t(c3)}) \sin(y+180) \cos(x+270) \end{array} \right] \\
 &= 1I_x K_a \cos^2(y) + 1I_{t(r4)} K_a \cos^2(y)
 \end{aligned}$$

The total translational force in the X- direction is then determined by summing the contributions from each row of coils 308:

20

$$\begin{aligned}
 F_{x(\text{total})} &= F_{x(r0)} + F_{x(r1)} + F_{x(r2)} + F_{x(r3)} + F_{x(r4)} \quad (52) \\
 &= 4I_x K_a [\sin^2(y) + \cos^2(y)] \\
 &= 4K_a I_x
 \end{aligned}$$

25 Control of the θ_z rotational movement is accomplished by selecting the current I_x in Eqs. 47 to 51. A similar approach is used to Y- direction translational control. Control of the rotational force is accomplished by selecting the current $I_{t(r)}$ in Eqs. 47 to 51. Torque control currents are determined as follows, with magnet array 304 located as shown in **Fig. 5**:

30

35

$$I_{t_{r0}}, I_{t_{r1}} = \frac{\text{Torque}_x}{12K_a}; \quad (53)$$

$$I_{t_{r2}} = \frac{\text{Torque}_x}{12K_a} - \frac{\text{Torque}_x}{12K_a} = 0; \quad (54)$$

5 $I_{t_{r3}}, I_{t_{r4}} = -\frac{\text{Torque}_x}{12K_a}; \quad (55)$

$$T_{x_{total}} = 6I_{t_r} K_a \sin^2(y) + 6I_{t_{r0}} K_a \sin^2(y) + 6I_{t_{r4}} K_a \cos^2(y) + \quad (56)$$

$$6I_{t_{r3}} K_a \cos^2(y)$$

10 $= 12I_{t_r} K_a [\sin^2(y) + \cos^2(y)]$
 $= 12K_a I_{t_r}$

$$I_{t_r} = \frac{\text{Torque}_x}{12K_a}$$

15 Turning now to the treatment of undesirable cross coupling between translational forces and θ_z rotational movement, it should first be noted that the symmetrical alignment of magnet array 304 with respect to coils 308, as shown in **Fig. 5**, permits translation in the X- direction without undesired torque. However, if the position of magnet array 304 with respect to coils 308 is changed, for example, to that shown in **Fig. 8**, driving 20 translational forces are no longer symmetrically generated and torque compensation is desired. Such compensation may be achieved with the following method: (1) applying an X- direction translational force to magnet array 304 and measuring the undesired torque; (2) normalizing the measured undesirable torque to create a predictor or model of the behavior with the undesired torque output preferably determined as a function of movement or offset 25 of magnet array 304 in the Y- direction, measured in pitch; (3) substantially canceling the undesired torque using the behavior model and the torque control of Eqs. 52 to 56.

30 An exemplar model of undesirable torque behavior is shown in **Fig. 9**, with undesired torque (measured in units of Newton-meters) graphed as a function of displacement (measured in units of pitch). For example, movement of +1 pitch results in undesired torque of about 50 N-pitch.

Further, an exemplar model of undesired torque compensation for F_x is shown in **Fig. 9A** and a compensation model for F_y is shown in **Fig. 9B**.

Referring to **Figs. 10** and **11**, torque and translation force outputs are shown in response to translation force compensation of 100 N-pitch and 100 N, respectively, as 35 magnet array 304 moves from $y = -1.5$ pitch to $y = 4.5$ pitch. Coupling between

translational force control and θ_z rotational movement control is shown to be substantially without coupling, with X- translation and θ_z rotation being independent.

Fig. 12 is a block diagram of a position control system 350 using an exemplary array of thirty-six coils 308 according to the present invention. Blocks **B₁** and **B₂**, for example, represent the undesired torque compensation maps shown graphically in Figs. 9A and 9B. The switch function of block **B₃** may be the switch function of Equations 44 and 45 as described above. The commutation block, **B₄**, may be governed by Equations 47 to 51, particularly the portion in square brackets. The thirty-six coil current output of amplifier block 352 is supplied to a position loop control at block **B₅**, at which time the force constant is multiplied by the above-mentioned bracketed commutation current in Equations 47 to 51. A total of twenty-five portions in square brackets are found in these equations, instead of 36, because the coil current is zero to position (R_5, C_5). Outputs x and y are measured in pitch, while output θ is measured in radians. Element 354 represents the amplitude of the control current for rows R_0 to R_5 , while element 356 represents the amplitude of the control current for columns C_0 to C_5 .

Fig. 13 is an elevational view, partially in section, showing a microlithographic apparatus 400 incorporating a planar motor-driven positioning stage 402 in accordance with the present invention. Microlithographic apparatus 400, such as described in U.S. Pat. No. 5,528,118 to Lee, includes an upper optical system 404 and a lower wafer support and positioning system 406. Optical system 404 includes an illuminator 408 containing a lamp **LMP**, such as a mercury vapor lamp, and an ellipsoidal mirror **EM** surrounding lamp **LMP**. Illuminator 408 also comprises an optical integrator, such as a fly's eye lens **FEL**, producing secondary light source images, and a condenser lens **CL** for illuminating a reticle (mask) **R** with uniform light flux. A mask holder **RST** holding mask or reticle **R** is mounted above a lens barrel **PL** of a projection optical system. A lens barrel **PL** is fixed on a part of a column assembly 410 which is supported on a plurality of rigid arms 412, each mounted on the top portion of an isolation pad or block system 414. Microlithographic apparatus 400 exposes a pattern of the reticle **R** onto a wafer **W**, while mask holder **RST** and positioning stage 402 are moving synchronously relative to illuminator 408.

Inertial or seismic blocks 416 are located on the system, e.g. mounted on arms 412. Blocks 416 can take the form of a cast box which can be filled with sand at the operation site to reduce the shipping weight of apparatus 400. An object or positioning stage base 418 is supported from arms 412 by depending blocks 416 and depending bars 420 and horizontal bars 422. Positioning stage 402 carrying wafer **W** is supported in a

movable fashion by positioning stage base 418. A reaction frame 424 carries a magnet array (not shown) and drives positioning stage 402 in cooperation with a moving coil array (not shown). Reaction frame 424 is isolated from positioning stage base 418 in terms of vibration relative to a foundation 426, when a force is generated as positioning stage 402 is 5 driven. Positioning stage 402 and/or mask holder RST can be driven by a planar motor such as planar motor 300 described above.

There are a number of different types of photolithographic devices. For example, exposure apparatus 400 can be used as a scanning type photolithography system which exposes the pattern from reticle R onto wafer W with reticle R and wafer W moving 10 synchronously. In a scanning type lithographic device, reticle R is moved perpendicular to an optical axis of lens assembly 404 by reticle stage RST and wafer W is moved perpendicular to an optical axis of lens assembly 404 by wafer stage 402. Scanning of reticle R and wafer W occurs while reticle R and wafer W are moving synchronously.

Alternately, exposure apparatus 400 can be a step-and-repeat type 15 photolithography system that exposes reticle R while reticle R and wafer W are stationary. In the step and repeat process, wafer W is in a constant position relative to reticle R and lens assembly 404 during the exposure of an individual field. Subsequently, between consecutive exposure steps, wafer W is consecutively moved by wafer stage 402 20 perpendicular to the optical axis of lens assembly 404 so that the next field of semiconductor wafer W is brought into position relative to lens assembly 404 and reticle R for exposure. Following this process, the images on reticle R are sequentially exposed onto the fields of wafer W so that the next field of semiconductor wafer W is brought into position relative to lens assembly 404 and reticle R.

However, the use of exposure apparatus 400 provided herein is not limited to 25 a photolithography system for semiconductor manufacturing. Exposure apparatus 400, for example, can be used as an LCD photolithography system that exposes a liquid crystal display device pattern onto a rectangular glass plate or a photolithography system for manufacturing a thin film magnetic head. Further, the present invention can also be applied 30 to a proximity photolithography system that exposes a mask pattern by closely locating a mask and a substrate without the use of a lens assembly. Additionally, the present invention provided herein can be used in other devices, including other semiconductor processing equipment, machine tools, metal cutting machines, and inspection machines.

The illumination source 408 can be g-line (436 nm), i-line (365 nm), KrF 35 excimer laser (248 nm), ArF excimer laser (193 nm) and F₂ laser (157 nm). Alternatively, illumination source 408 can also use charged particle beams such as x-ray and electron

beams. For instance, in the case where an electron beam is used, thermionic emission type lanthanum hexaboride (LaB₆) or tantalum (Ta) can be used as an electron gun.

Furthermore, in the case where an electron beam is used, the structure could be such that either a mask is used or a pattern can be directly formed on a substrate without the use of a
5 mask.

With respect to lens assembly 404, when far ultra-violet rays such as the excimer laser are used, glass materials such as quartz and fluorite that transmit far ultra-violet rays are preferably used. When the F₂ type laser or x-ray is used, lens assembly 404 should preferably be either catadioptric or refractive (a reticle should also preferably be a
10 reflective type), and when an electron beam is used, electron optics should preferably comprise electron lenses and deflectors. The optical path for the electron beams should be in a vacuum.

Also, with an exposure device that employs vacuum ultra-violet radiation (VUV of wavelength 200 nm or lower, use of the catadioptric type optical system can be
15 considered. Examples of the catadioptric type of optical system include the disclosure Japan Patent Application Disclosure No. 8-171054 published in the Official Gazette for Laid-Open Patent Applications and its counterpart U.S. Patent No. 5,668,672, as well as Japan Patent Application Disclosure No. 10-20195 and its counterpart U.S. Patent No. 5,835,275. In these cases, the reflecting optical device can be a catadioptric optical system
20 incorporating a beam splitter and concave mirror. Japan Patent Application Disclosure No. 8-334695 published in the Official Gazette for Laid-Open Patent Applications and its counterpart U.S. Patent No. 5,689,377 as well as Japan Patent Application Disclosure No. 10-3039 and its counterpart European Patent Application EP 0816892 A2 also use a reflecting-refracting type of optical system incorporating a concave mirror, etc., but without
25 a beam splitter, and can also be employed with this invention. The disclosures in the above-mentioned U.S. patents, European patent application, as well as the Japan patent applications published in the Official Gazette for Laid-Open Patent Applications are incorporated herein by reference.

Further, in photolithography systems, when linear motors (see U.S. Patent
30 Nos. 5,623,853 or 5,528,118) are used in a wafer stage or a reticle stage, the linear motors can be either an air levitation type employing air bearings or a magnetic levitation type using Lorentz force or reactance force. Additionally, the stage could move along a guide, or it could be a guideless type stage which uses no guide. The disclosures in U.S. Patent Nos. 5,623,853 and 5,528,118 are incorporated herein by reference.

Alternatively, one of the stages could be driven by a planar motor, which drives the stage by electromagnetic force generated by a magnet unit having two-dimensionally arranged magnets and an armature coil unit having two-dimensionally arranged coils in facing positions. With this type of driving system, either one of the

5 magnet unit or the armature coil unit is connected to the stage and the other unit is mounted on the moving plane side of the stage.

Movement of the stages as described above generates reaction forces which can affect performance of the photolithography system. Reaction forces generated by the wafer (substrate) stage motion can be mechanically released to the floor (ground) by use of

10 a frame member as described in U.S. Patent No. 5,528,118 and published Japanese Patent Application Disclosure No. 8-166475. Additionally, reaction forces generated by the reticle (mask) stage motion can be mechanically released to the floor (ground) by use of a frame member as described in U.S. Patent No. 5,874,820 and published Japanese Patent Application Disclosure No. 8-330224. The disclosures in U.S. Patent Nos. 5,528,118 and

15 5,874,820 and Japanese Patent Application Disclosure No. 8-330224 are incorporated herein by reference.

As described above, a photolithography system according to the above-described embodiments can be built by assembling various subsystems, including each element listed in the appended claims, in such a manner that prescribed mechanical

20 accuracy, electrical accuracy and optical accuracy are maintained. In order to maintain the various accuracies, prior to and following assembly, every optical system is adjusted to achieve its optical accuracy. Similarly, every mechanical system and every electrical system are adjusted to achieve their respective mechanical and electrical accuracies. The process of assembling each subsystem into a photolithography system includes mechanical interfaces,

25 electrical circuit wiring connections and air pressure plumbing connections between each subsystem. Needless to say, there is also a process where each subsystem is assembled prior to assembling a photolithography system from the various subsystems. Once a photolithography system is assembled using the various subsystems, total adjustment is performed to make sure that every accuracy is maintained in the complete photolithography

30 system. Additionally, it is desirable to manufacture an exposure system in a clean room where the temperature and humidity are controlled.

Further, semiconductor devices can be fabricated using the above-described systems, by the process shown generally in **Fig. 14**. In step **501** the device's function and performance characteristics are designed. Next, in step **502**, a mask (reticle) having a

35 pattern is designed according to the previous designing step, and in a parallel step **503**, a

wafer is made from a silicon material. The mask pattern designed in step 502 is exposed onto the wafer from step 503 in step 504 by a photolithography system described hereinabove consistent with the principles of the present invention. In step 505 the semiconductor device is assembled (including the dicing process, bonding process and 5 packaging process), and then finally the device is inspected in step 506.

Fig. 15 illustrates a detailed flowchart example of the above-mentioned step 504 in the case of fabricating semiconductor devices. In step 511 (oxidation step), the wafer surface is oxidized. In step 512 (CVD step), an insulation film is formed on the wafer surface. In step 513 (electrode formation step), electrodes are formed on the wafer by vapor 10 deposition. In step 514 (ion implantation step), ions are implanted in the wafer. The above-mentioned steps 511 -514 form the preprocessing steps for wafers during wafer processing, and selection is made at each step according to processing requirements.

At each stage of wafer processing, when the above-mentioned preprocessing steps have been completed, the following post-processing steps are implemented. During 15 post-processing, initially, in step 515 (photoresist formation step), photoresist is applied to a wafer. Next, in step 516 (exposure step), the above-mentioned exposure device is used to transfer the circuit pattern of a mask (reticle) to a wafer. Then, in step 517 (developing step), the exposed wafer is developed, and in step 518 (etching step), parts other than residual photoresist (exposed material surface) are removed by etching. In step 519 20 (photoresist removal step), unnecessary photoresist remaining after etching is removed.

Multiple circuit patterns are formed by repetition of these preprocessing and post-processing steps.

It will be apparent to those skilled in the art that various modifications and variations can be made in the methods described, in the stage device, the control system, the 25 material chosen for the present invention, and in construction of the photolithography systems as well as other aspects of the invention without departing from the scope or spirit of the invention.

While various descriptions of the present invention are described above, it should be understood that the various features can be used singly or in any combination 30 thereof. Therefore, this invention is not to be limited to only the specifically preferred embodiments depicted herein.

Further, it should be understood that variations and modifications within the spirit and scope of the invention may occur to those skilled in the art to which the invention pertains. For example, magnet arrays and coil arrays having a different number of magnets 35 and/or coils, respectively, from those discussed in detail herein may be used in accordance

with the principles of the present invention. Accordingly, all expedient modifications readily attainable by one versed in the art from the disclosure set forth herein that are within the scope and spirit of the present invention are to be included as further embodiments of the present invention. The scope of the present invention is accordingly defined as set forth
5 in the appended claims.

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